Preheating in Palatini Higgs inflation and related plateau models

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Cosmology from Home 2020
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Based on arXiv 1902.10148, 2007.03484

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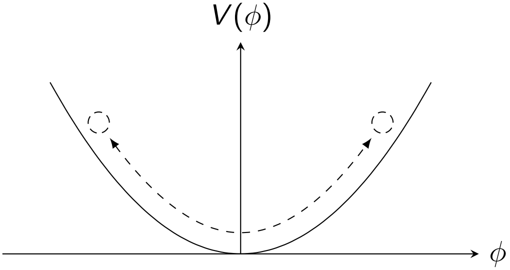
Introduction

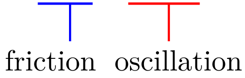
- After cosmic inflation, inflaton field oscillates around potential minimum
- Reheating: transition from inflation to early radiation dominated universe
- Preheating: non-perturbative particle production in this transition

Oscillating inflaton

- Standard example: ϕ^2 potential

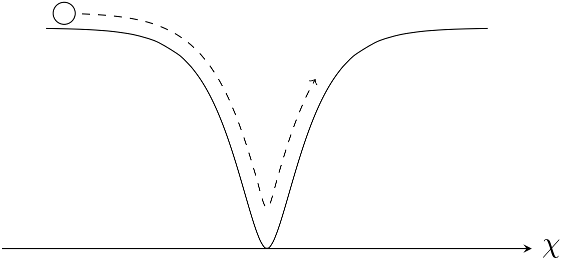


$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$



Oscillating inflaton

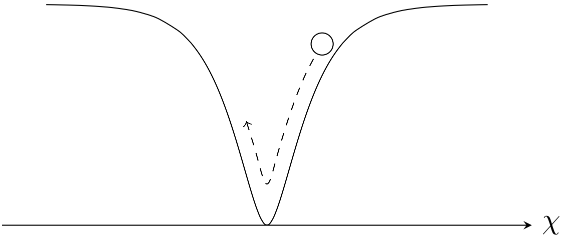
- More realistic model: plateau inflation



- Usually, oscillation amplitude decays quickly due to Hubble friction

Oscillating inflaton

- More realistic model: plateau inflation



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Oscillating inflaton

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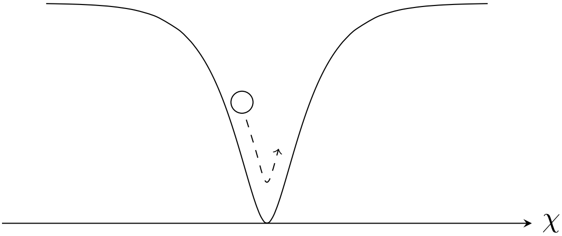

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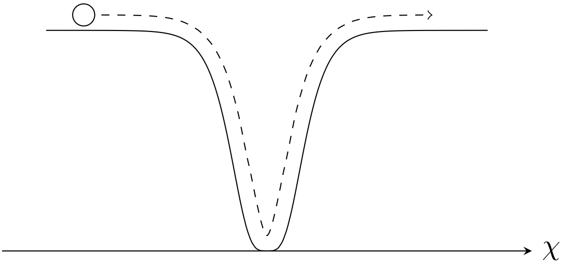
Oscillating inflaton

- However, there's a class of models with special behaviour:



- Oscillation amplitude stays almost constant!

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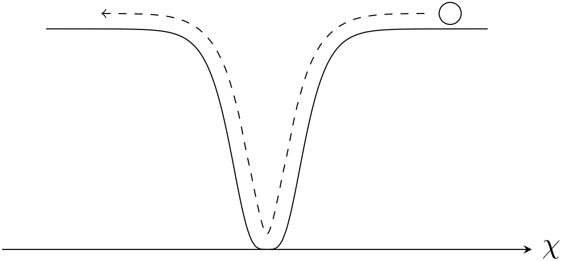

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Oscillating inflaton

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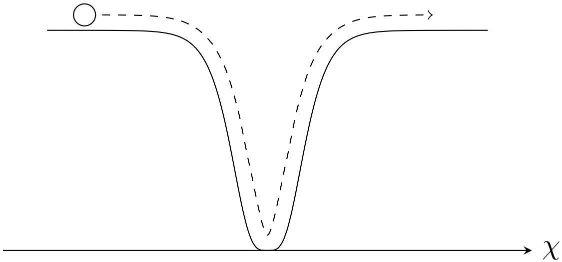


- Oscillation amplitude stays almost constant!

Slow decay of oscillation amplitude

- Cause: extreme flatness of potential, with very sharp decline to bottom
- Energy loss in one semi-oscillation:

$$3H^2 = \frac{1}{2}\dot{\phi}^2 + V(\phi)\,, \quad \ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0 \quad \Rightarrow \dot{H} = -\frac{1}{2}\dot{\phi}^2$$

$$\Rightarrow \frac{\Delta H}{H} = \frac{\sqrt{3}}{\sqrt{V(\phi_{\rm max})}} \int_0^T dt \left(-\frac{1}{2}\dot{\phi}^2\right) =$$

$$\frac{\sqrt{3}}{\sqrt{V(\phi_{\rm max})}} \int_{-\phi_{\rm max}}^{\phi_{\rm max}} d\phi \left(-\frac{1}{2}\dot{\phi}\right) \approx -\sqrt{6} \int_{-\phi_{\rm max}}^{\phi_{\rm max}} d\phi \sqrt{1 - \frac{V(\phi)}{V(\phi_{\rm max})}}$$

- For these potentials, $\Delta H/H \ll 1$

Slow decay of oscillation amplitude

- True for flat potentials, $V \propto 1 - Ae^{-\phi/\phi_0}$, with $\phi_0 \ll 1$
- E.g. $V = V_0 \tanh^n \xi\phi$ with $\xi \gg 1$
- E.g. Palatini Higgs inflation [1902.10148], Palatini R^2 inflation, ...
- Typically accompanied by suppressed tensor-to-scalar ratio $r \propto \phi_0$

Particle production

- Free field mode function:

$$\ddot{Q}_k + 3H\dot{Q}_k + \underbrace{\left[\frac{k^2}{a^2} + m^2(\phi)\right]}_{\omega_k^2} Q_k = 0$$

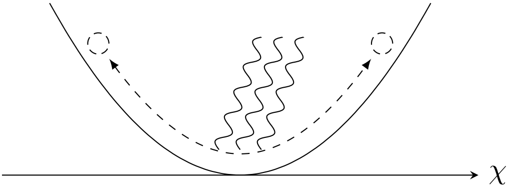
- For constant ω_k, standard solution:

$$a^{3/2}Q_k = \frac{\alpha_k}{\sqrt{2\omega_k}} e^{-i\int^t \omega_k(t')\,dt'} + \frac{\beta_k}{\sqrt{2\omega_k}} e^{i\int^t \omega_k(t')\,dt'}$$

- Adiabatic vacuum: $\alpha_k = 1$, $\beta_k = 0$
- Non-vacuum states: $n_k = |\beta_k|^2$

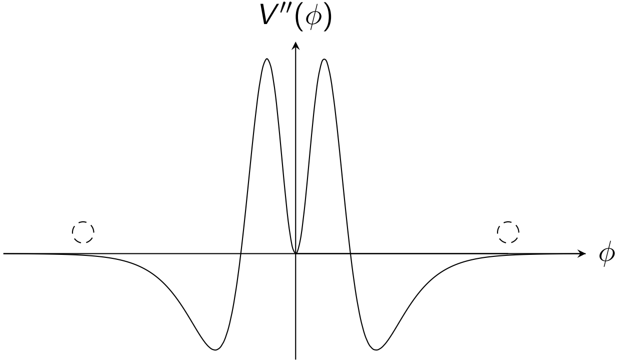
Usual case: parametric resonance

- Adiabaticity condition $|\dot{\omega}_k|/\omega_k^2 \ll 1$ broken near the bottom of the potential
- For certain Fourier modes: explosive particle production



Our case: tachyonic preheating

- If $m^2 < 0 \Rightarrow \omega_k^2 < 0$, mode function grows exponentially: $Q_k \propto e^{\sqrt{-\omega_k^2}t}$
- Possible for inflaton perturbations with $m_\phi^2 = V''$



Our case: tachyonic preheating

- Particle concept is ill-defined, but we can calculate energy density in perturbations:

$$\frac{\rho_{\rm pert}}{\rho_{\rm B}} = \frac{1}{3H^2 M_P^2} \int_{k_{min}}^{k_{max}} \frac{dk\, 4\pi k^2}{(2\pi)^3} \frac{1}{2} \left[|\dot{Q}_k|^2 + \left(\frac{k^2}{a^2} + V''(\phi) \right) |Q_k|^2 \right]$$

- Numerical calculations: significant fraction of energy density in perturbations after only a few oscillations, less than one e-fold

Example: Palatini Higgs inflation

- Action:

$$S = \int d^4x\sqrt{-g}\left[-\frac{1}{2}\left(M^2 + \xi h^2\right) g^{\mu\nu}R_{\mu\nu} + \frac{1}{2}g^{\mu\nu}\partial_\mu h\partial_\nu h - \frac{\lambda}{4}h^4\right]$$

- Standard procedure: Weyl transformation to Einstein frame

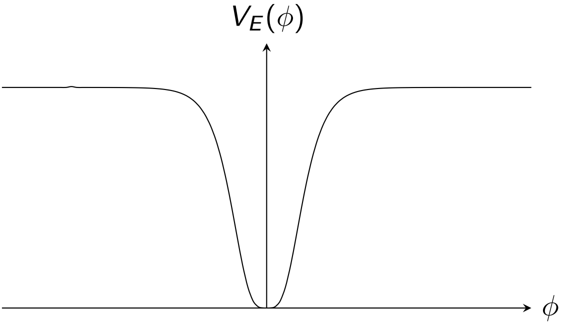
$$g_{\mu\nu} = g_{E\mu\nu}\left(1 + \frac{\xi h^2}{M^2}\right)^{-2}, \quad R_{\mu\nu} = R_{E\mu\nu}\,, \quad \frac{d\phi}{dh} = \frac{1}{\sqrt{1+\xi h^2}}$$

Example: Palatini Higgs inflation

- Einstein frame action:

$$S = \int d^4x \sqrt{-g_E}\left[-\frac{1}{2}M^2 g^{E\mu\nu} R_{E\mu\nu} - \frac{1}{2} g^{E\mu\nu} \partial_\mu\phi\partial_\nu\phi - V_E(\phi)\right]$$

- Einstein frame potential: $V_E = \frac{\lambda}{4\xi^2}\tanh^4(\sqrt{\xi}\phi)$



CMB predictions

- Parameter values and observables: [0803.2664]

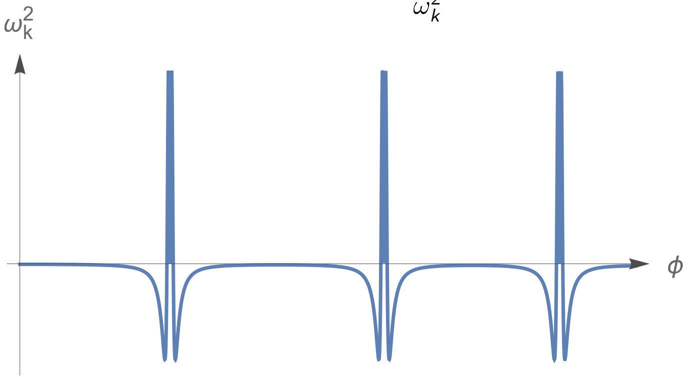
$$\xi \approx 3.8 \times 10^6 \lambda N^2 \sim 10^9$$

$$n_s \approx 1 - \frac{2}{N} \approx 0.96\,, \qquad r \approx \frac{2}{\xi N^2} \sim 10^{-12}$$

Palatini Higgs preheating

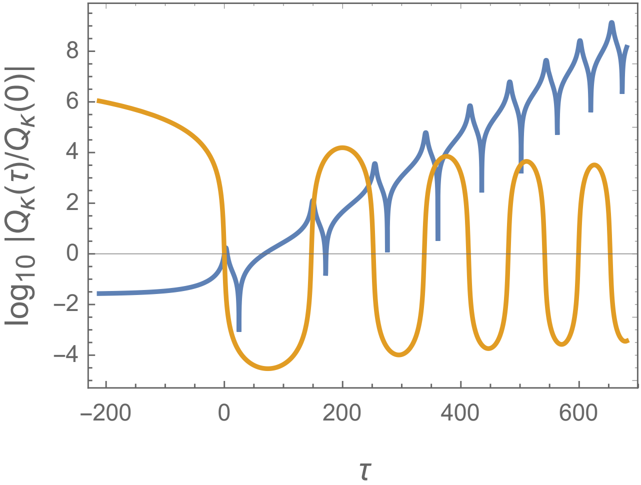
- Higgs perturbations:

$$\ddot{Q}_k + 3H\dot{Q}_k + \underbrace{\left[\frac{k^2}{a^2} + V_E''(\phi)\right]}_{\omega_k^2} Q_k = 0$$



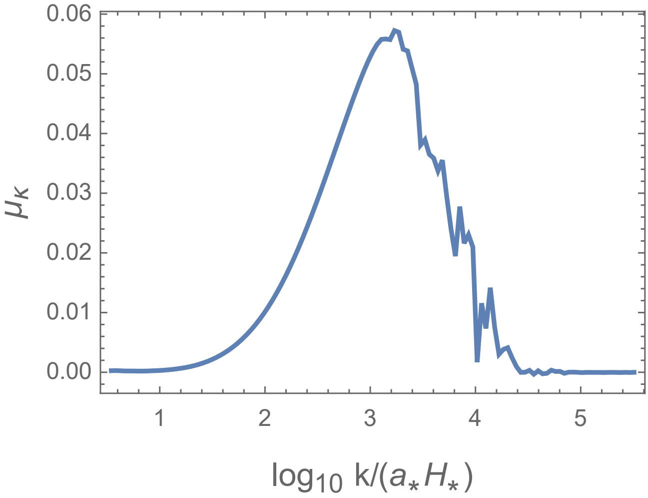
Palatini Higgs preheating

- Typical tachyonic mode function: $Q_k \propto e^{\mu_k \tau}$



Palatini Higgs preheating

- Growth index depends on k:



Adding a spectator field

- Add to action:

$$S_\chi = \int d^4x\sqrt{-g}\left[-\frac{1}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - \frac{1}{2}m_\chi^2\chi^2\right].$$

- Weyl transformation to Einstein frame, with field redefinition:

$$\sigma \equiv \Omega^{-1}\chi\,, \qquad \Omega = \sqrt{1+\xi h^2}$$

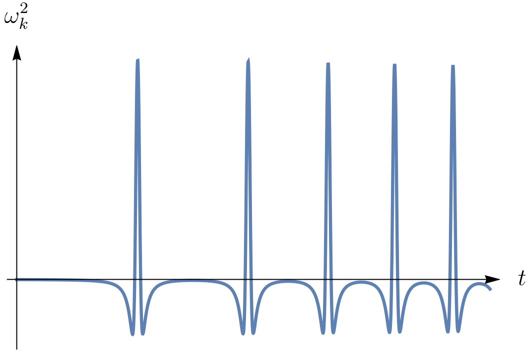
$$\Rightarrow S_\sigma = \int \mathrm{d}^4x\sqrt{-g}\left[-\frac{1}{2}g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma - g^{\mu\nu}\frac{\sigma\partial_\mu\sigma\partial_\nu\Omega}{\Omega}\right.$$

$$\left.-\frac{1}{2}\left(\frac{m_\chi^2}{\Omega^2} + g^{\mu\nu}\frac{\partial_\mu\Omega\partial_\nu\Omega}{\Omega^2}\right)\sigma^2\right]$$

Adding a spectator field

- Spectator perturbations:

$$\ddot{\sigma}_k + 3H\dot{\sigma}_k + \underbrace{\left[\frac{k^2}{a^2} + \frac{m_\chi^2}{\Omega^2} + 3H\frac{\dot{\Omega}}{\Omega} - 2\left(\frac{\dot{\Omega}}{\Omega}\right)^2 + \frac{\ddot{\Omega}}{\Omega}\right]}_{\omega_k^2}\sigma_k = 0\,,$$



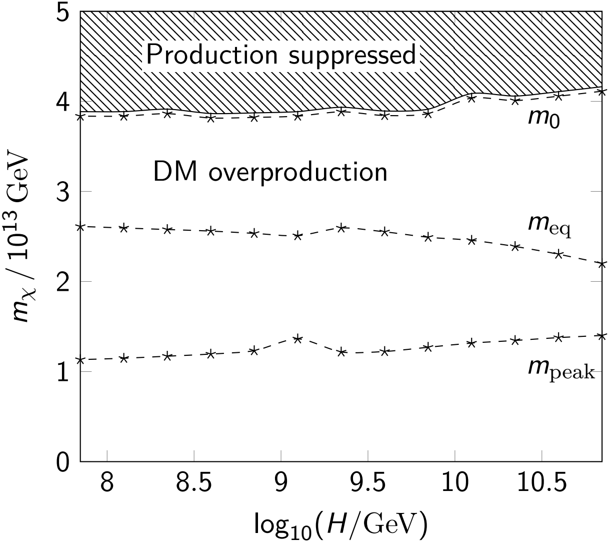
Palatini Higgs preheating

- Energy density transferred from inflaton to perturbations in less than one e-fold
- Higgs production always tachyonic, efficient; spectator production tachyonic if

$$m_\chi \lesssim m_{\rm tac} \equiv \sqrt{\frac{2\lambda}{\xi}} \sim 10^{13}\ \mathrm{GeV}$$

- Possibility for superheavy dark matter

Palatini Higgs preheating



Conclusions

- A class of models exists, where inflaton returns to plateau repeatedly during reheating
- Consequence: fast tachyonic production of inflaton particles
- Consequence: possibility to excite (superheavy) spectator fields as well

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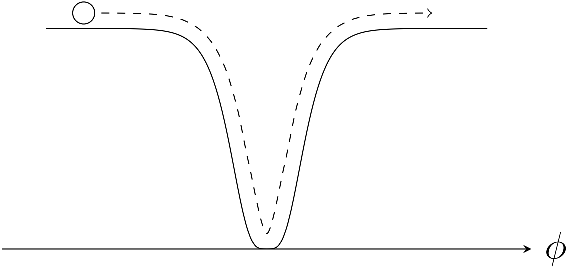
- Inflaton returns to plateau repeatedly



- Tachyonic production of inflaton and spectator field particles (super-heavy DM?)